Fuel Injector with Hydraulic Flow Control

Field of the Invention

The present invention relates generally to fuel injectors, and more particularly to fuel injectors configured to regulate the rate of fuel injection.

Background of the Invention

Motor vehicles are required to comply with increasingly stringent limits on noise and emissions imposed by federal, state, and local regulatory bodies. Since published research has demonstrated noise and emissions from an internal combustion engine are influenced by the time history of the fuel flow rate through the injector spray holes, or injection rate shape, considerable effort has been expended to adjust and control the shape of this injection flow rate curve in response to the specific requirements of a particular engine application. Most hydraulic methods of regulating the flow rate at the injector involve either the use of a partial restriction or alternate flow path upstream from the nozzle spray holes to regulate the amount of fuel to reach the exit of the injector. The function of the alternate flow path in prior designs has typically been to divert a portion of the fuel to either an accumulator or the pump fuel supply system via a second external outlet located on the injector. A number of different approaches to implement these two methods have been taken.

Some injectors include two springs for biasing the needle valve toward its closed position. U.S. Patent number 4,938,193 to R. Raufeisen et al. entitled *Fuel Injection Nozzle* provides one example of this type. The two springs allow the injector to open in two stages. The needle valve opens a first distance under the influence of only one spring at a first pressure substantially lower than required to overcome the second spring preload. During this first stage of injection, the flow rate through the injector is throttled at the needle valve tip. Once the second

stage opening pressure is reached, the needle valve moves to the maximum travel limit imposed by the needle lift adjusting screw to allow unrestricted flow to reach the injector spray holes. For many fuel systems the pump plunger motion and resulting rate of pressure rise in the system vary with engine speed. At idle and low engine speeds where the rate of pressure rise is low, sufficient time is available for the first stage operation to significantly influence the initial rate of fuel injection. As engine speed increases, the transition to second stage operation occurs more rapidly and lessens or eliminates the first stage regulation. Consequently, two spring systems typically provide rate-shaping at lower engine speeds, but not distinct pilot and main injections.

A further approach to regulate the flow rate through the use of throttling is outlined in U.S. Patent number 4,987,887 to W. Kelly entitled *Fuel Injector Method and Apparatus.* Two stage injector operation is obtained by metering fuel through a reduced radial clearance for a portion of needle valve travel before increasing the flow path area to provide unrestricted flow to the spray holes at the maximum limit of needle valve travel. With this type of flow path area to needle valve positional relationship, both rate regulation, and in some fuel systems utilizing a low initial rate of pressure increase, pilot injection, may be obtained with this type of injector in a design that can be manufactured at a relatively low cost.

An implementation scheme for diverting a portion of the fuel pump delivery is discussed in U.S. Patent number 5,647,536 to Yen et al entitled *Injection Rate Shaping Nozzle Assembly for a Fuel Injector.* Needle valve position is used to open and close flow rate limited spill paths within the injector to connect high pressure supply and low pressure drain circuits in the fuel system for a period of time during the injection. The flow rate of fuel entering the combustion chamber is claimed to change in a predetermined time varying manor as a result of this injector design.

Since power output, emission requirements, and economic constraints vary considerably with different engine applications, methods in addition to the above-discussed prior art are still required. One area of particular relevance is discussed in U.S. Patent number 6,526,939 to Reitz et al. entitled *Diesel Engine Emissions Reduction by Multiple Injections Having Increasing Pressure.* For this approach, electronic control of fast acting valves on common rail fuel systems is used to produce multiple injections for the reduction of particulate and NOx emissions. While the added expense and complexity associated with this type of fuel system may be justifiable for some engine applications, others may benefit from a different more simplistic and robust hydraulic control method to create either rate shaping, or rate shaping with pilot or multiple injections through the use of flow path closure within the injector.

Summary of the Invention

A hydraulic flow control exemplary of aspects of the present invention is incorporated into the needle valve and needle bore adjacent the high-pressure fuel inlet passage to the injector. The fuel inlet passage communicates with a fuel inlet control volume surrounding the needle bore and defined between upper and lower metering edges. The needle valve is provided with a first control volume that interrupts the cylindrical outside surface of the needle valve head into an upper portion and a lower portion that functions as a metering ring. An aspect of the invention relates to a fuel flow passage through the needle valve connecting the first control volume to the second control volume of the injector below the head of the needle valve. The flow control defines pilot and main fuel flow paths that are dependent upon needle valve position.

The metering ring on the needle valve is positioned so that a valve annulus or clearance communicates between the fuel inlet control volume and the first control volume of the needle valve when the needle

valve is in the closed position. A pilot fuel flow path is defined from the fuel inlet control volume through the valve annulus, first control volume and fuel flow passage to the second control volume. This pilot fuel flow path is open when the needle valve is in the closed position and gradually closes as the needle valve moves away from the nozzle seat. A primary fuel flow path directly from the fuel inlet control volume to the second control volume opens when the metering ring on the needle valve is raised above the lower metering edge of the fuel inlet control volume. The metering ring on the needle valve closes the pilot fuel flow path before valve movement opens the primary fuel flow path to interrupt fuel flow at a mid-range of valve travel.

Operation of the flow control is affected by the shape of the high pressure fuel pulse, e.g., the pressure vs. time curve of the pulse. For many fuel injection systems, the pulse shape varies with engine speed. At idle and low engine speeds, pressure increases relatively slowly with time so that an initial hydraulic pressure wave through the pilot fuel flow path does not have sufficient energy to move the needle valve through the mid-range of valve travel to open the primary fuel flow path. A pilot injection occurs when the needle valve returns to its closed position where a second, stronger hydraulic pressure wave moves the needle valve to its fully open position.

At higher engine speeds, the pressure of the high pressure pulse increases more rapidly, thereby giving the initial hydraulic pressure wave sufficient energy to move the valve through the mid-range of valve travel to open the primary fuel flow path. As a result, pilot injection is typically more pronounced at lower engine speeds with frequently only a change to the injection rate shape occurring at higher speeds.

The volume of fuel in each high pressure pulse also affects operation of the flow control. Under low speed, light load conditions where each pulse is of a small volume, the pilot injection may be larger than the subsequent "primary" injection. This is due to the limited overall volume of fuel being injected. As the volume of each high

pressure pulse increases, the pilot injection represents a smaller portion of the total volume of fuel being injected.

Brief Description of the Drawings

Figure 1 is a sectional view through a fuel injector incorporating a hydraulic flow control according to aspects of the present invention;

Figure 2 is an enlarged view of the nozzle body of the fuel injector of Figure 1;

Figures 3 and 4 are enlarged sectional views of a first embodiment of a hydraulic flow control according to aspects of the present invention where fuel flow passages through the needle valve are shown in phantom and cut away, respectively;

Figures 5 and 6 are enlarged sectional views of a second embodiment of a hydraulic flow control according to aspects of the present invention where fuel flow passages through the needle valve are shown in phantom and cut away, respectively;

Figures 7 and 8 are enlarged sectional views of a further embodiment of a hydraulic flow control according to aspects of the present invention where fuel flow passages through the needle valve are shown in phantom and cut away, respectively;

Figures 9 through 11 are enlarged sectional views illustrating fluid flow pathways defined by the hydraulic flow control at three of valve operational positions; and

Figure 12 is a graph of flow area as a function of needle valve position for an injector equipped with a flow control according to aspects of the present invention.

Detailed Description of Exemplary Embodiments

With reference to the drawings wherein like numerals represent like parts throughout the figures, a fuel injector incorporating a hydraulic flow control 30 according to aspects of the present invention is generally designated by the numeral 10. In general structure and function, the

fuel injector 10 is of the type in which an nozzle holder body 14 defines a needle bore 11 extending between a nozzle seat 24 and a needle guide 50. A nozzle body 20 encloses one end of the needle bore 11 and defines spray holes 22 through which fuel is injected. A needle valve 46 is received in the needle bore 11 for axial reciprocation therein between a closed position (shown in Figure 1) and an open position. A needle valve shank 42 connects the needle valve head 44 to the needle valve tip 40. The needle valve 46 is biased toward the closed position by a pressure adjusting spring 52. A needle lift adjusting screw 54 defines the axial travel the needle valve 46 is permitted between its closed and open positions. The compression force of pressure adjusting spring 52 and the axial travel of the needle valve 46 are adjustable in a conventional manner.

The needle guide 50 of the needle bore has a greater diameter than the nozzle seat 24, providing a differential area on which fuel accumulating in the second control volume 12 operates to open the needle valve 46 against the bias of the pressure adjusting spring 52. An exemplary guide diameter is approximately .16in and an exemplary seat diameter is approximately .08in for a guide/seat ratio of approximately 2:1. The second control volume tends to be larger for increased guide diameters.

An aspect of the present invention relates to moving the fuel inlet passage 60 from an axial position where it would open directly into the second control volume 12 to an axial position corresponding with the needle valve head 44. The fuel inlet passage 60 communicates with a fuel inlet control volume 62 surrounding the needle bore 11. The needle valve head 44 is modified to include a first control volume 47 in the form of a circumferential groove and a fuel flow passage 45a, 45b, 45c connecting the first control volume 47 to the second control volume 12 below the head 44.

The needle valve head 44 is closely received in the upper portion of the needle bore 11 which acts as a needle guide 50 for controlling

needle valve motion during axial reciprocation. The circumferential fuel inlet control volume 62 interrupts the needle guide 50 into an axially extended upper guide portion 50a and an axially truncated lower guide portion 50b. The fuel inlet control volume 62 is defined between upper and lower metering edges 63, 65, the lower metering edge 65 of the fuel inlet control volume 62 corresponding to an upper edge of the needle guide lower portion 50b.

The generally cylindrical outside surface of the needle valve head 44 is interrupted by a first control volume 47 into upper and lower outside surface portions. The head lower surface portion extends between an upper control edge 53 corresponding to the lower edge of the first control volume 47 and a lower control edge 51. The head lower surface portion operates as a metering ring 43 whose control edges 53, 51 interact with the metering edges 63, 65 of the fuel inlet control volume 62 to regulate fluid flow between the inlet 60 and the second control volume 12. The outside surface of the needle valve head 44 and the metering ring 43 are fit to adjacent surfaces on the needle valve bore 50a, 50b to minimize fluid leakage but allow free motion of the needle valve 46.

The number and shape of the fuel passage(s) 45a, 45b, 45c defined by the needle valve 46 are not limited to those forms illustrated and discussed herein. Figures 5 and 6 illustrate the fluid flow passage 45b as a single diagonal bore communicating between the first control volume 47 and the second control volume 12 axially below the needle valve head 44. Figures 7 and 8 alternatively illustrate two diagonal bores 45c commencing at the first control volume 47 and communicating with the second control volume 12 below the needle valve head 44. Figures 3 and 4 illustrate more complex fluid flow passages 45a formed from connecting angled bores and including metering orifices 49 communicating directly between the fuel inlet control volume 62 and the fluid flow passages 45a. These metering orifices 49 are an optional feature that permit adjustment of needle valve response by allowing

high-pressure fuel to enter the second control volume 12 regardless of needle valve position.

With the exception of Figures 10 and 11, the Figures illustrate the needle valve in its closed position. In the closed position, the lower control edge 51 of the metering ring overlaps the lower guide portion 50b to block fluid communication between the fuel inlet control volume 62 and the second control volume 12. The upper control edge 53 of the metering ring 43 is a predetermined axial distance below the upper metering edge 63 of the fuel inlet control volume 62 to define a fluid flow clearance 16 in the form of a valve annulus. When in the closed position and for an initial axial movement of the needle valve 46, fuel flows from the fuel inlet control volume 62 through the fluid flow clearance 16 and fuel passages 45a, 45b, 45c to the second control volume 12. Pressure increases in the second control volume 12 and moves the needle valve 46 away from its closed position. Axial movement of the needle valve 46 gradually closes the fluid flow clearance 16 above the metering ring 43. As shown in Figures 9 and 10, this initial phase of needle valve movement provides a pilot injection by lifting the needle valve tip 40 away from the nozzle seat 24 and injecting fuel through the spray holes 22 until fuel flow is interrupted by closure of the fluid flow clearance 16.

Continued axial movement of the needle valve 46 away from the nozzle seat 24 opens a second or "primary" fuel flow path when the lower control edge 51 of the metering ring 43 clears the lower metering edge 65 of the fuel inlet control volume 62 as shown in Figure 11. This opens an unrestricted fuel flow path directly from the fuel inlet control volume 62 to the second control volume 12. The interruption of fuel flow which occurs when the metering ring 43 spans the upper and lower metering edges 63, 65 of the fuel inlet control volume 62 provides a pilot injection at low engine operating speeds. At low engine speeds, an initial hydraulic pressure wave propagates through the pilot fluid flow pathway (shown in Figure 9) to produce an initial needle valve movement and pilot injection of fuel. At low engine speeds, the energy of this initial

pressure wave is insufficient to move the needle valve 46 through the mid-range of travel shown in Figure 10 and open a primary fluid flow pathway. Upon reaching its mid-range position, closure of the pilot fuel flow pathway causes pressure in the second control volume to decline, allowing the needle valve to reverse direction to its closed position. This reopens the pilot fluid flow path, which is exposed to hydraulic pressure that has been increasing since closure of the pilot fuel flow pathway. This second hydraulic pressure wave will have sufficient energy to move the needle valve 46 from its closed position, through the mid-range position where neither fluid flow path is open, to its fully open position as shown in Figure 11. In the fully open position, an unrestricted fluid flow path is opened between the bottom metering edge 51 of the metering ring and the bottom metering edge 65 of the fuel inlet control volume 62.

At higher engine speeds, the initial hydraulic pressure wave will have sufficient energy to move the needle valve directly to the fully open position illustrated in Figure 11. Thus at higher engine speeds, the pilot injection effect of the hydraulic flow control of the present invention will decline or disappear entirely to provide only a change to the rate-shape of injection.

Figures 3 and 4 illustrate a hydraulic flow control including optional metering orifices connecting the fuel inlet control volume to the fluid flow passage or passages. Such metering orifices can be used to adjust the rate-shape of injection by preventing complete loss of flow through the injector during mid-range valve travel. Adjustments to the size, shape and number of fluid passages through the needle valve also have an impact on behavior of the hydraulic flow control.

Experimentation indicates that the length of the axial dimension of the fluid flow clearance 16 relative to the axial length of the overlap 18 of the metering ring and the needle guide lower portion is important to providing a pilot injection. In the exemplary embodiment, the clearance 16 should be substantially smaller than the overlap 18. A ratio of 1:3

clearance 16 to overlap 18 has been shown to produce a distinct pilot injection over a useful range of low engine speeds. An exemplary axial clearance is .0015in and an exemplary axial overlap is .0045in. The axial dimension of the fluid flow clearance 16 provides an initial fluid flow area as shown in Figure 12. Figure 12 graphically compares the flow area through the fuel injector to the axial position of the needle valve. The flow area of the pilot fuel flow path decreases to near zero to create a fluid seal when the needle valve position exceeds the initial clearance axial dimension 16. The area of the primary fuel flow path increases from a needle valve position exceeding the overlap length 18. Maximum valve lift in the illustrated embodiment is limited by a needle lift adjusting screw to approximately .0156in (0.4mm).

While exemplary embodiments of the foregoing invention have been set forth for purposes of illustration, the foregoing description should not be deemed a limitation of the invention herein. Accordingly, various modifications, adaptations and alternatives may occur to one skilled in the art without departing from the spirit and the scope of the present invention.